

Astrophysical Science and Technology



Physics & Advanced
Technologies



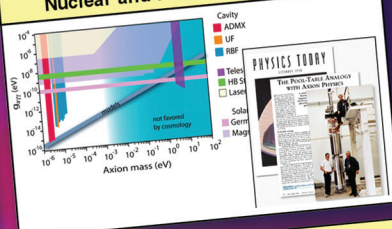
Physics and Advanced Technologies Directorate
Lawrence Livermore National Laboratory

The Physics and Advanced Technologies (PAT) Directorate at Lawrence Livermore National Laboratory helps ensure the scientific excellence and vitality of the major Laboratory programs through its leadership role in performing basic and applied, multidisciplinary research and development with programmatic impact.

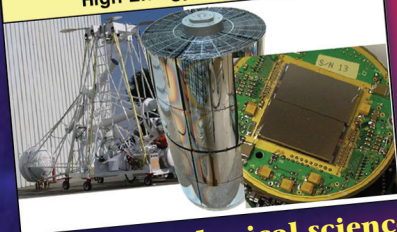
Observational Astronomy S&T



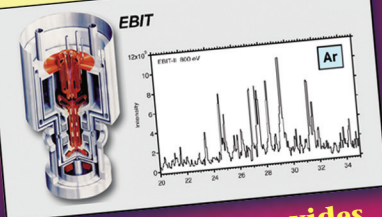
Nuclear and Particle Astrophysics



High Energy Astrophysics



Laboratory Astrophysics



**Astrophysical science and technology provides
a direct coupling to the science of stockpile
stewardship, the technology of national security,
and the capabilities of LLNL.**

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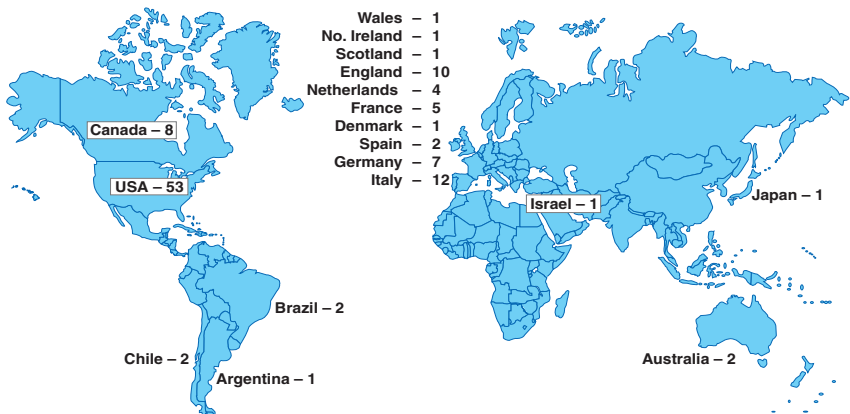
Introduction

We undertake astrophysical science and technology R&D because of its close alignment with and tight coupling to the science of stockpile performance, the technology of national security, and the capabilities of LLNL. Overlapping areas include detectors, surveillance, data handling and mining, and even materials science techniques (we use the most advanced analytic electron microscope available). In our theoretical work the overlaps are in radiation transport, coupled radiation-hydrodynamics, plasma physics, and the science of extreme conditions. High performance computing is required for large scale, integrated simulations involving similar physics. Of course, both

astrophysics and programs require similar calibration technologies, x-ray science and optics.

We are emphasizing four thrust areas; Stars from Birth to Death, the Primitive Solar System, Giant Planets, and the High Energy Universe. In each of these we perform computational simulations and modeling, laboratory scale experiments, and develop and deploy advanced observational tools.

The following sections highlight our recent and current work, which provides approximately 20% of our more than 500 per year peer-reviewed publications. These publications involve collaborations with 115 institutions (universities, laboratories, and companies) in 16 foreign countries and 22 states.



Our collaborations in astrophysics involve groups from many countries

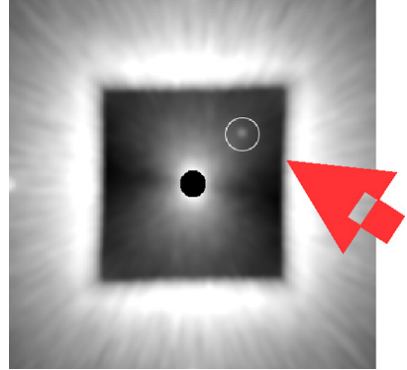
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Observational Astronomy Science and Technology

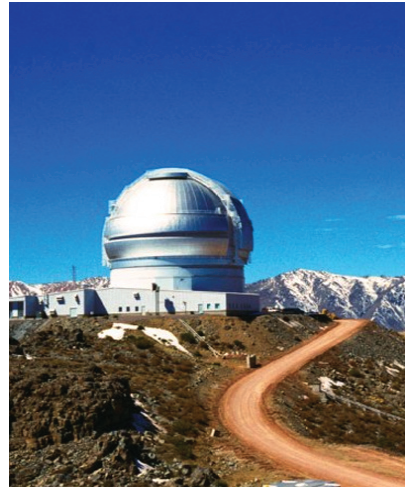
Adaptive Optics for Exoplanet Imaging

The LLNL astronomical Adaptive Optics (AO) program was started in the 1990's, and developed the first operational sodium laser guide star at the Lick Observatory. This was followed by the construction of major portions of the Keck AO system and Keck laser guide star. LLNL was a founding member of the NSF Center for Adaptive Optics in 1999. Our current AO programs includes high power laser beam control, remote sensing, ophthalmology, and astronomy; the astronomy component thrives with two newly funded projects (LSST, see later, and Gemini, this section) and the continuation of the work at the Keck Observatory.

The detection of exosolar planets is a major astronomical priority; an image of an exosolar planet will be the next major step forward in studying other solar systems. To do this with a ground based system requires what has been called "Extreme" Adaptive Optics systems. The problem is to remove the light from the adjacent star, allowing the planet to be seen against the background. This in turn means increasing the strehl (the ratio between the peak intensity of an image divided by the peak intensity of a diffraction-limited image with the same total flux) from around 0.6 in a normal AO system, to around 0.98. We are leading an international team on a funded project to add a 2000-actuator AO system to the Gemini South Observatory in Chile. First light for the ~\$20M project will be ~2009.



A simulation of a star and planet (arrowed) system as seen with the extreme AO system on Gemini



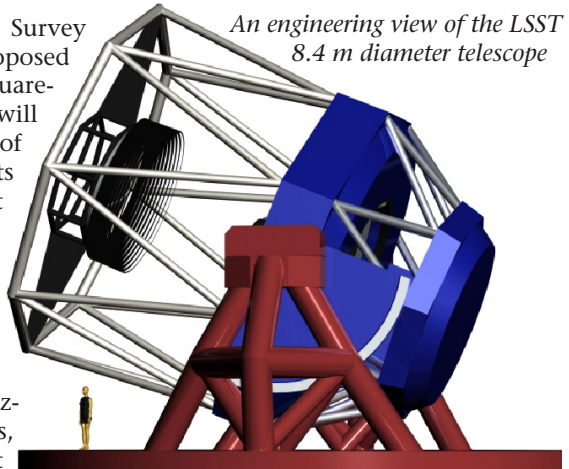
A view of the Gemini South Observatory, where optics will be sited

Observational Astronomy Science and Technology

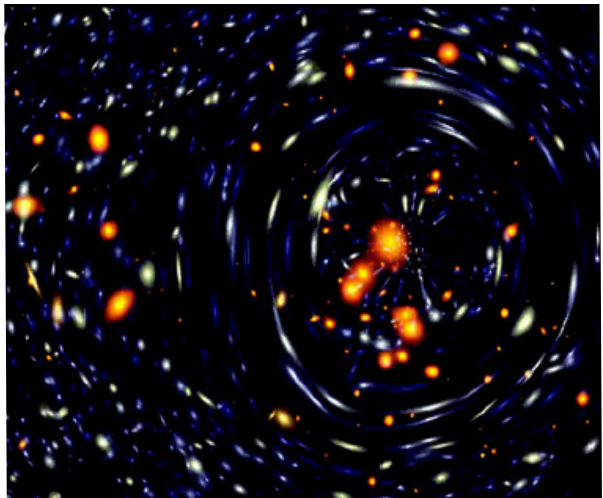
The Large Synoptic Survey Telescope (LSST)

The Large Synoptic Survey Telescope (LSST) is a proposed ground-based 8.4 m, 10 square-degree-field telescope that will provide digital imaging of faint astronomical objects across the entire sky, night after night. It will cover the available sky every three nights, providing movies of objects that change or move on rapid timescales: exploding supernovae, potentially hazardous near-Earth asteroids, and distant Kuiper Belt objects. The images will also be used to trace the apparent distortions in the shapes of remote galaxies produced by dark matter, providing tests of the mysterious dark energy.

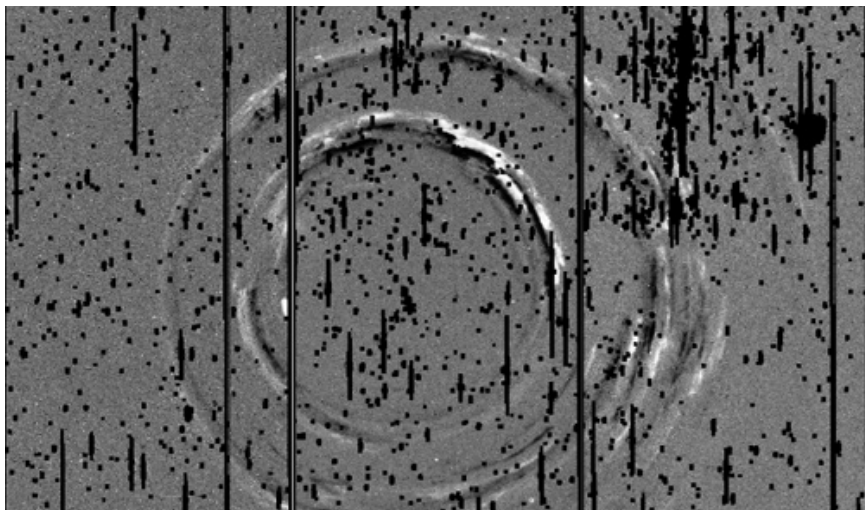
The LSST Corporation currently has 12 Institutional Members. NSF has funded the first year of a 4 year, \$14.2M award. The LSST Director is J. Anthony Tyson, University of California, Davis; LLNL provides the Project-Manager, and is involved in much of the challenging R&D: Optical design and wavefront control, Gigapixel Camera with 1 second read-out, Performance Models and Precursor Surveys, Data



Management (an astounding ~30 TB/night or 50 PB in ten years), Optical coatings, and "End to End" simulations. These simulations will model the sky, atmosphere, and LSST instrument to validate the



Model results of how galaxy shapes will be distorted by intervening dark matter, in the strong lensing limit



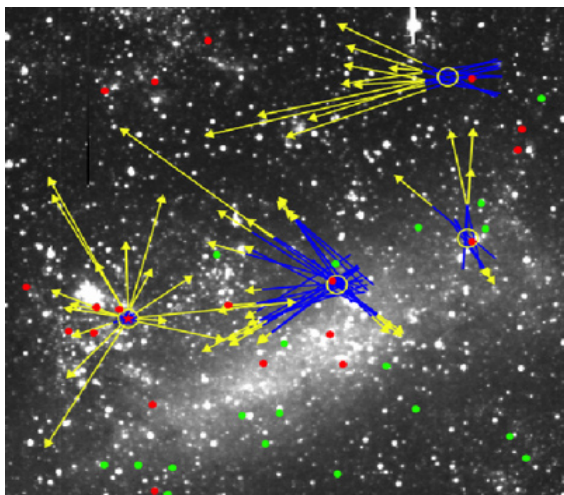
SN 1987A: Light echoes made visible by difference image subtraction

dark matter and dark energy science goals.

While first light from LLST is not anticipated until 2013, we are already developing techniques to deal with the torrent of data, and applying these to existing astronomical data bases. An example is image subtraction, (or difference image analysis), that allows Poisson noise-limited photometry of changes in crowded fields. Using

these techniques, applied to the SuperMACHO data base, we have discovered many 'new' light echoes. Light echoes are produced when a light pulse from a stellar source is reflected by interstellar or circumstellar material such as dust, and can appear as a luminous ring or rings that expand at what can appear to the observer as faster than the speed of light. We have analyzed their movement and projected

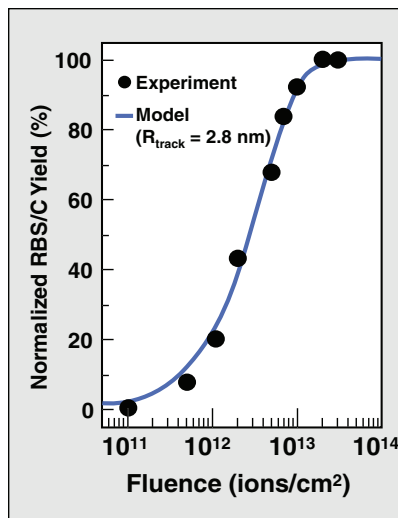
back to find the source. In the figure green/red represent historical nova/supernova remnants, and yellow/blue vectors are projections forward/backward.



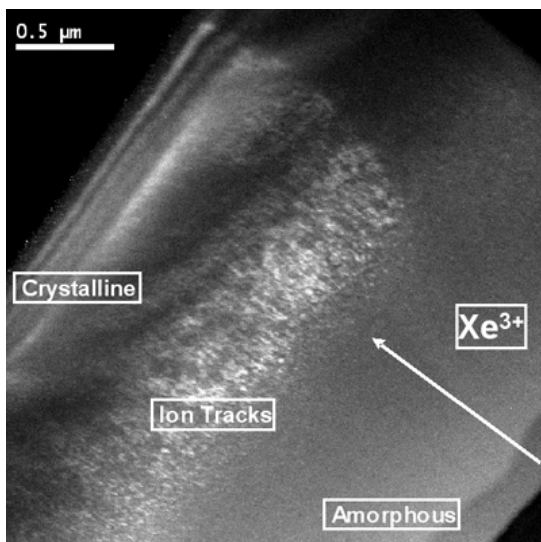
Projecting back echo systems to find the source. Three project back to known type 1a supernova remnants with ages between 200 and 1500 years old, a rate much higher than predicted

Galaxies grow through merging, triggering the collapse of interstellar clouds, star formation, and supernovae. Dust grains, formed in stellar winds and supernovae, are thought to play a crucial role in this process by providing a sub micron 'staging area' for molecular formation. The molecules themselves are needed to radiate energy – only molecular vibrations can cool the interstellar clouds from a few 100 K to 10 K. Crystalline grains do not provide sufficient surface area to cool fast enough, so amorphous grains are required, and indeed are seen in the interstellar medium.

Ultra-violet light, x-rays, cosmic rays and shocks are all thought to affect dust grains. To test the hypothesis that cosmic rays can cause amorphization, we have used an ion beam to simulate cosmic rays to study damage. The figure shows results of irradiating crystalline forsterite (Mg_2SiO_4) with Xe^{3+} at 10 MeV. Damage is measured using He^+ Rutherford Backscattering, to find amorphization at $\sim 10^{13}$ ions/cm². This fluence of Xe is equivalent to that expected for the Fe in cosmic rays over 70 Million years. Next we will address how surface chemistry changes with fluence, and the effect of higher energies.



Damage as measured by Rutherford Backscatter on crystalline forsterite, g as a function of fluence



High Resolution Transmission Electron Microscopy of an irradiated sample of forsterite

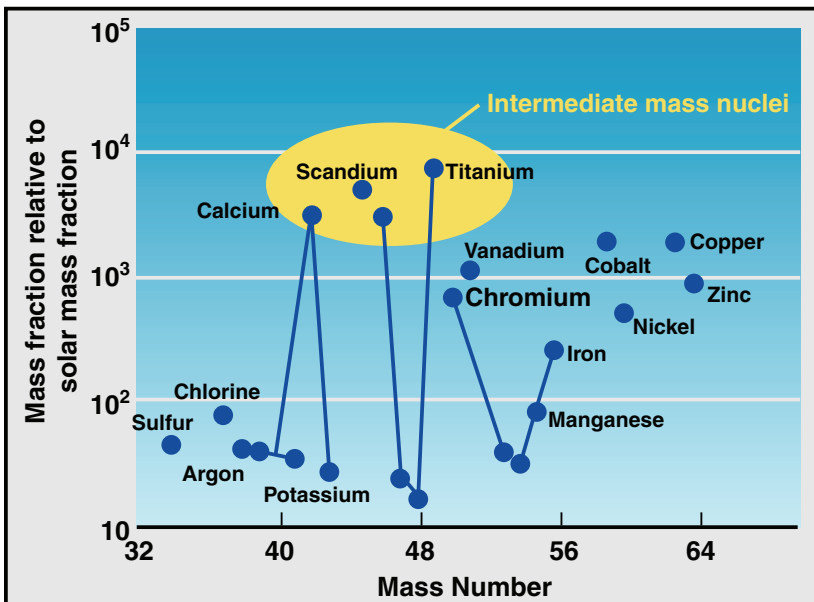
Nuclear and Particle Astrophysics

Supernovae and Nucleosynthesis

Nuclear astrophysics tries to understand the origin of elements encountered in everyday life. It is well known that most isotopes heavier than helium were synthesized in the hot interiors of stars. Our own sun and solar system contain ashes strewn across the galaxy by about a hundred exploding supernovae. Though galactic chemical evolution is understood in broad detail, and even the precise origins of many nuclei are well established, some enigmatic riddles remain. Among these are the origin of nature's most neutron and

proton-rich isotopes, the nuclear burning occurring in the uncertain inner environments of supernovae, the imprint of black holes on the fossil record carried by ancient stars and the role of neutrinos in nucleosynthesis.

As part of the SciDAC supernova effort led by Stan Woosley our group has made contributions to the understanding of nucleosynthesis in the most extraordinary conditions realized in nature. Along with researchers from UC Santa Cruz, the University of Chicago and Los Alamos we have presented some of



Nucleosynthesis in a wind emitted from the surface of the black hole accretion disk powering a gamma ray burst. Our calculations predict about enough yield to account for the present day galactic inventory of some of the intermediate mass isotopes (Astrophysical Jo. Letters, 2004).

the worlds best models for X-ray bursts. These occur as a neutron star accretes matter from a stellar companion and burns protons to form elements as heavy as Tellurium. For core-collapse supernovae occurring as neutrinos sap pressure from the degenerate iron core of a massive star we have collaborated with members of the Max Planck Institute to study nucleosynthesis in ejecta emitted in the first seconds after the birth of a neutron star. This work led to a possible resolution of a long-standing mystery about over-production of $N=50$ closed shell nuclei. Lastly, a collaboration with NC State and Berkeley astrophysicists led to predictions for the contribution of Gamma Ray Bursts to galactic chemical evolution. Gamma Ray Bursts are among nature's most extraordinary explosions - they briefly outshine all of the stars in the universe combined. Though the origin of these events is not certain there is growing evidence linking them to the deaths of massive stars and the formation of a black hole. We found that some interesting intermediate-mass isotopes - including scandium and germanium 64, as well as the long enigmatic $A=130$ r-process isotopes that include silver and cadmium,

can be synthesized in Gamma Ray Bursts. The figure below shows our calculations for intermediate mass nuclei synthesized in winds from a black hole accretion disk.

Our efforts in understanding nucleosynthesis are complemented by research into more basic aspects of nuclear and particle physics. This builds on a dedicated reaction modeling effort serving both astrophysics and applied physics. Among our accomplishments in these areas are the development of new cross section evaluations critical for understanding observation of radioactive isotopes seen with satellites, an improved understanding of thermal weak processes for heavy nuclei and calculations of the neutrino signature from the passage of a relativistic jet through a star.

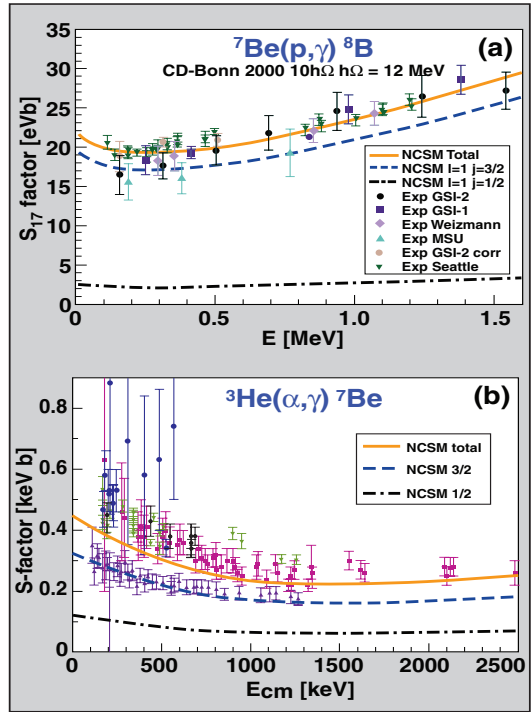
Given disks, another possibility for nucleosynthesis exists. We expect magnetically driven localized instabilities, which can quickly carry proton-rich 'magnetic bubbles' of material from the interior to the surface. This provides a source of gold, silver and other neutron-rich elements, solving an outstanding puzzle that cannot be explained by the usual mechanisms.

A Fundamental Theory of Light Ion Reactions

Our objective is to predict the structure of light nuclei and to describe reactions involving light nuclei, starting from fundamental interactions among nucleons. This is important because it will allow us to calculate S-factors (cross sections) from fundamental physics, i.e. it will allow us to obtain cross sections for reactions where measurements are very difficult or impossible. One important astrophysics application will be to better understand our sun and its neutrino production. For this we need to know the S factor for the reaction ${}^7\text{Be}(p,\gamma){}^8\text{B}$ to better than 9%, whereas current experimental uncertainties are $>20\%$. The present lack of knowledge in the ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ cross section is the most important uncertainty in the solar model predictions of the neutrino fluxes in the p-p chain, and the S factor here needs to be known to better than 5%.

For $A = 3$ and 4 nuclei there are many exact methods to calculate the structure of the system, but for $A > 4$ few methods exist. We are developing the Ab Initio No-Core Shell Model (NCSM) for structure studies and extending it to describe nuclear reactions (see P. Navratil and E. Ormand, Phys.

Rev. Lett. 88, 152502 (2002)). The starting point is the many-body Schroedinger equation, which includes the realistic high-quality nucleon-nucleon potentials and allows for three-nucleon interactions. We have applied the approach to both the reactions noted above; in one case we find results within the experimental uncertainties, and in the other we find better agreement with some data sets than with others.



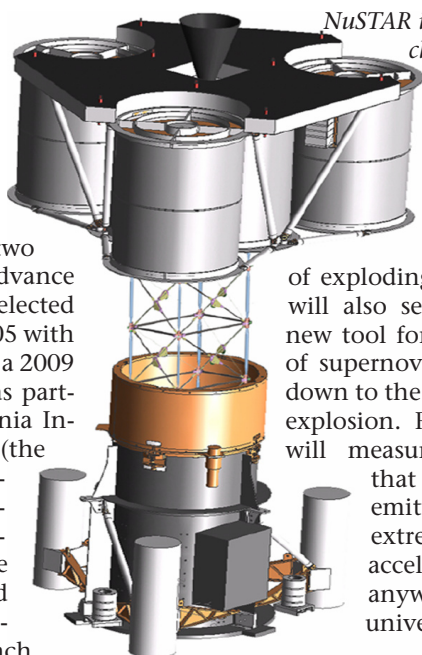
Comparisons of the ab initio model predictions (orange lines) and experiment, for the S-factors in two reactions: (a) ${}^7\text{Be}(p,\gamma){}^8\text{B}$ and (b) ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$

High Energy Astrophysics

NuSTAR, The Nuclear Spectroscopic Telescope Array

NuSTAR is an explorer-class satellite project, to fly a set of three hard x-ray telescopes, with more than an order of magnitude advance in spatial and spectral resolution and two orders of magnitude advance in sensitivity. It was selected by NASA in January 2005 with initial confirmation for a 2009 launch. Livermore has partnered with the California Institute of Technology (the lead institution on NuSTAR), Columbia University, the Danish National Space Center, the Jet Propulsion Lab and several other institutions to build and launch NuSTAR. We are particularly involved in the x-ray optics and the detector, and were part of the team that tested these systems on the 9 year balloon-born HEFT mission, that successfully flew in 2005. Low cost, grazing incidence optics coated with nested, depth-graded multilayers are used to achieve the large collection areas required.

NuSTAR's most important scientific result will be the first deep maps of the hard x-ray sky. Today the best images of the 20 to 40 keV sky are dominated by the bright glow of unresolved sources. NuSTAR will do much better, detecting emission from individual black holes that reside in the centers of galaxies. Because hard x-rays escape from the



NuSTAR is an explorer-class satellite project, to fly a set of three hard x-ray telescopes

deepest layers of exploding stars, NuSTAR will also serve as a useful new tool for looking inside of supernovae and probing down to the very core of the explosion. Finally, NuSTAR will measure hard x-rays that are copiously emitted by the most extreme particle accelerators found anywhere in the universe.

The nested, depth graded, multilayer x-ray optical mirrors used on HEFT, a testbed for NuSTAR



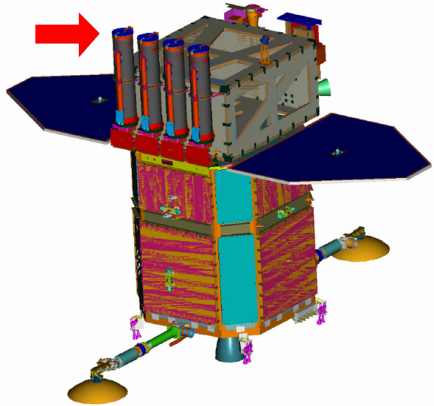
High Energy Astrophysics

Multilayer-coated EUV Telescopes for the Solar Dynamics Observatory

The Solar Dynamics Observatory (SDO) is part of NASA's Living with a Star program. Launch is set for April 2008, in an orbit at 36,000 km inclined geosynchronous. Our involvement is in one of the three instruments on board, the Atmospheric Imaging Assembly (AIA), funded by NASA and managed by Lockheed Martin Solar and Astrophysics Lab. The AIA is designed to provide an unprecedented view of the solar corona, taking images that span at least 1.3 solar diameters in multiple wavelengths nearly simultaneously, at a resolution of 1 arcsecond, field of view of 41 arcminutes and a cadence of 10 seconds or better. LLNL is implementing the extreme ultra-violet (EUV) multilayer coatings on the large-area AIA telescope optics and this requires extending the state-of-the-art multilayer science and technology that we have previously developed.



Multilayer development is performed at LLNL's large-area DC-magnetron sputtering system



The AIA on the Instrument module, shown with doors open, consists of four nearly identical science telescopes (arrowed)

Spinoffs from the development will enhance EUV and x-ray multilayer optics for high-energy physics, the National Ignition Facility, and the Linac Coherent Light Source, all areas or facilities in which we are involved.

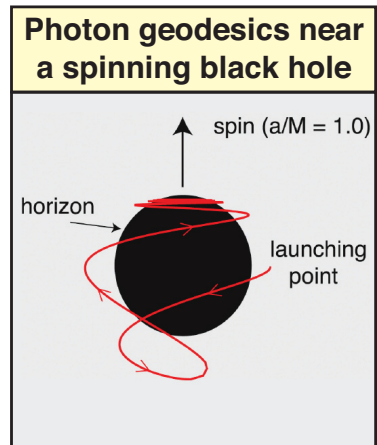
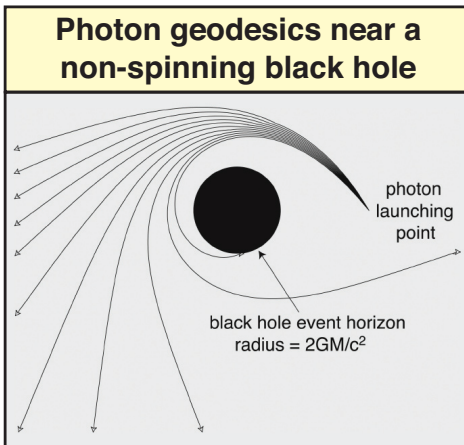
The AIA is intended to resolve fundamental observational ambiguities between solar magnetic field evolution (indirectly seen as moving coronal loops) and thermal and density changes in adjacent loop atmospheres that outline the magnetic field. With our collaborators, we are now in the process of multilayer-coating and characterizing the 7 EUV channels.

Structure and Spectroscopy of Black Hole Accretion Disks

We have developed a new x-ray diagnostic of the physics near black holes. It is based on recent observations of black hole systems, which show that x-ray line emission is modified by special and general relativistic effects. The emission arises from accretion of material onto the black hole, and the x-rays probe the behavior of matter in the strong field limit of gravitation. The emission depends on disk kinematics (velocity, inclination, radius) and disk structure (line composition, radiation transport,

radial emissivity profile). We have completed a computer code and are now using it to study problems including: the full radiation transport of resonant Auger destruction, the effect of returning radiation on fluorescence emission and disk structure, and the effect of changing the geometrical distribution of ionizing radiation sources.

The source of observed photons is not intuitive, as can be seen by the trajectories shown in the figure.



Photon trajectories near a black hole, either stationary or spinning, show that relativistic effects are crucial to understanding where one is observing

The Axion

Most of the matter in the universe is dark, i.e. cannot be detected because it emits no photons. Its existence is inferred from the trajectories of stars, galaxies and galaxy clusters, and explains how gravity could amplify the small fluctuations in the Cosmic Microwave Background to form the large-scale structures that make up today's universe.

Particle physics provides 3 dark-matter candidates: neutrinos, Weakly Interacting Massive Particle (WIMPs), and axions, a hypothetical elementary particle proposed to explain the absence of an electrical dipole moment for the neutron. The axion has no electric charge, no spin, and interacts with ordinary matter (electrons, photons, quarks, etc.) only very weakly. Even though the axion - if it exists - should have only a tiny mass, axions would have been produced abundantly in the Big Bang, and relic axions are an excellent candidate for the dark matter in the universe.

Our experiment attempts to detect axions trapped in the dark halo of our galaxy; we expect about



The axion experimental hardware and members of the axion research team

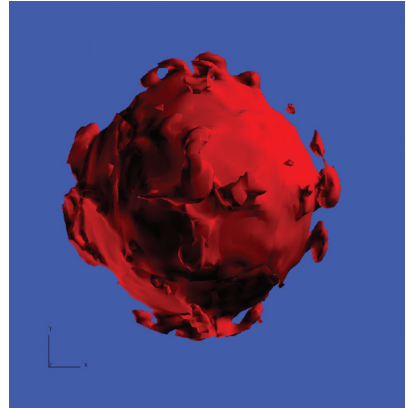
10^{13} axions per cubic centimeter locally. In the presence of a static magnetic field, there is a small probability for axions to decay into microwave photons via the "Primakoff effect." Our detector consists of a high-Q tunable microwave cavity inside a large superconducting magnet about 1 meter long with a bore diameter of

Stellar Evolution — Djehuty

Essentially all previous research on stellar structure and evolution has assumed spherical symmetry, leaving important physical processes like convection, differential rotation, and magnetic fields to be incorporated through approximation. Djehuty, named after the Egyptian god of wisdom, writing, and time measurement, is a computer code for simulating stars in three dimensions, eliminating many previously essential approximations. With it, we have begun to examine stages of stellar structure and evolution that were not previously accessible to real study.

The helium core flash is just such a stage. Most stars evolve through a Giant structure where a degenerate helium core is surrounded by a hydrogen burning shell and envelope. When conditions in such a core permit the helium to begin burning a critical event occurs called the helium core flash. Because the core is degenerate, the fusion energy raises the temperature without a significant pressure increase. As a result, the core does not expand and cool for stability. With an energy production rate proportional to the 20th power of the temperature, there existed the possibility of a catastrophic thermonuclear runaway, and stellar survival depended on the time development of small hot bubbles and their buoyancy.

In one-dimensional simulations, the post helium core flash evolution depends dramatically on



A three dimensional contour of fixed ^{18}O mass fraction, which serves as a tracer of element production and convective distribution in the helium burning shell

poorly constrained elements of the convection model. The predicted end states ranged from quiescent core helium burning stars, to completely mixed or disrupted stars. In the first true calculation of the helium core flash, Djehuty finds the time development of convection is sufficiently rapid to stabilize the ignition, and avoid core envelope mixing (much less stellar disruption). We are currently extending these simulations to stars with rotating cores, investigating a new mechanism for mixing on the giant branch, studying disk systems with bipolar outflow such as cataclysmic variables, and have studied a new type 1 like supernovae mechanism.

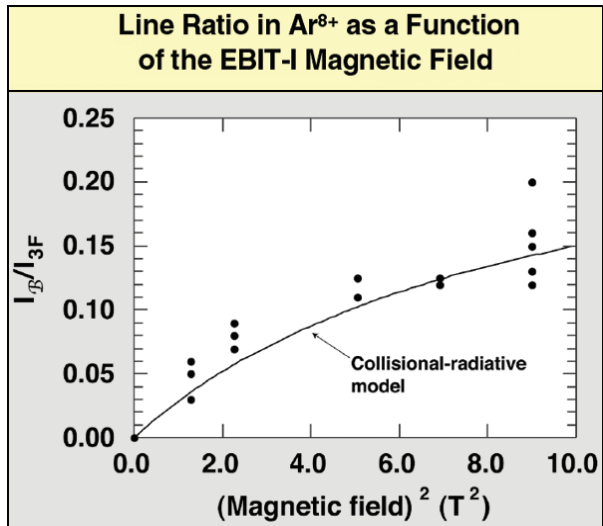
Laboratory Astrophysics

Electron Beam Ion Trap (EBIT) and Laboratory Astrophysics

This group was established in 1991 as a collaboration with UC Berkeley, centered around the electron beam ion trap at LLNL. It has grown to be a highly visible and published group, that includes collaborators from around the country and several other facilities. Student participation and education plays a significant role. Recent studies include laboratory simulation of cometary x-ray emission, x-ray studies supporting XMM and Chandra, and stellar flare simulations on tokamaks. The facility has just been fitted with new instrumentation, including a micro-calorimeter x-ray detector from a space flight mission, and high-resolution grating spectrometers, and these have enabled our latest successes. Recent highlights include: Spectral catalogues of high-Z ions for astrophysical diagnostics in the extreme ultraviolet, Discovery of an x-ray line diagnostic of magnetic field strength, Resolution of a stellar opacity puzzle, Simulation of cometary x-ray emission, and A new measurement in quantum electrodynamics – an extension of quantum mechanics – that is 10 times

more precise than any recent measurements, demonstrating that the theory works even under extreme conditions.

For the future, the group is extending its expertise to observational astrophysical. Group members are also members of the ASTRO-E2 Science Working Group, and members have been awarded 140 ksec for observing the Ophiuchus Cluster of galaxies. The group is also pursuing the possibility to perform part of the Con-X calibration, and have started collaborations on sounding rocket experiments to observe the solar corona in the x-ray and EUV region.



A line ratio in Ar^{8+} is shown as a function of the EBIT-I magnetic field. This suggests use as an observational magnetic field diagnostic

Laboratory Astrophysics

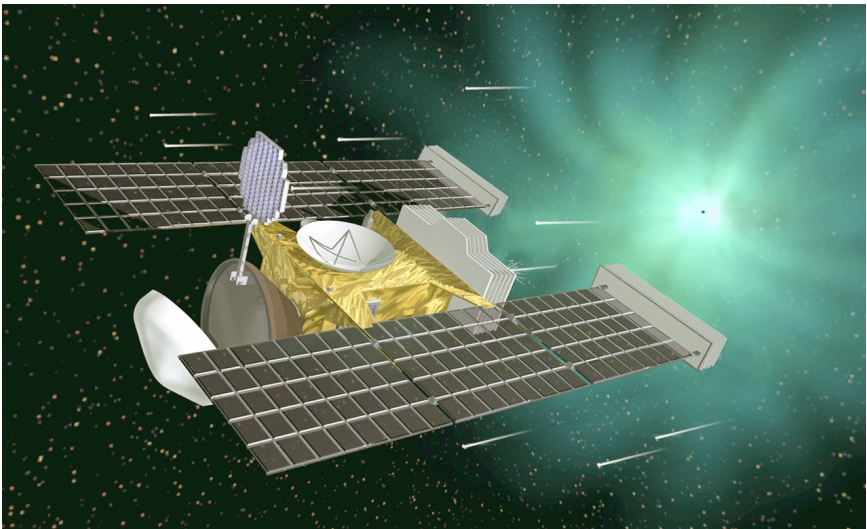
Astro-materials

Astro materials – meteorites, micro-meteorites and interplanetary dust particles (IDP's), contain cosmically-primitive solar nebula and presolar solids from circumstellar and interstellar environments. Active collection techniques include very high flying aircraft, and NASA's STARDUST mission. This spacecraft, launched in February 1999, flew by comet WILD 2's nucleus in January 2005, through a halo of gases and dust, collecting cometary dust particles released from the surface just hours before. The spacecraft will return less than a milligram of particles to earth in 2006, when a Laboratory team will be analyzing them. Because Wild 2 circles in the Kuiper belt, beyond Neptune, it has not been altered by warming and collisions that affect matter in the

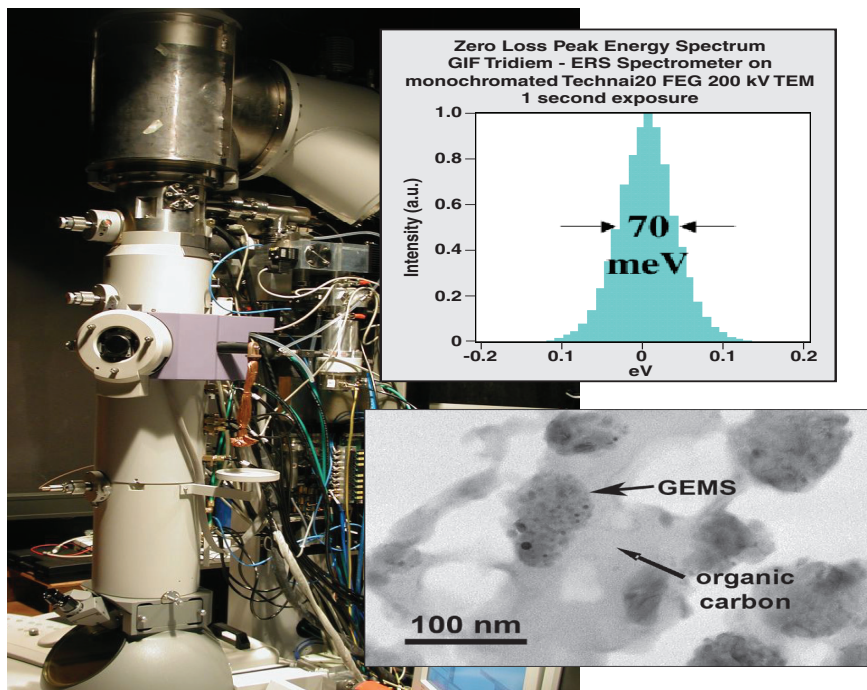
inner solar system, so we think it holds information about the solar system's building blocks.

Analysis of the returned particles will be performed using the Laboratory's state of the art instrumentation: e.g. the Center for Accelerator Mass Spectrometry (CAMS), secondary-ion mass spectrometer (nano-sims), focused ion beam (FIB), and a NASA-funded electron microscope or "superSTEM". We are already deploying these to analyze existing IDP's (from aircraft collection), and are finding new and often unique information on galactic chemical evolution, and in so doing we are establishing a new branch of astrophysics.

For example, we have explained the ubiquitous '2175 feature', that blocks light from stars



Artist's conception of Stardust mission's comet WILD 2 encounter



The NASA-funded superSTEM, and a 200-keV brightfield transmission electron micrograph of organic carbon and GEMS within chondritic IDP

from reaching the Earth due to the absorption of light by dust in the interstellar medium (Bradley et al., *Science* **307**, 244-247 (2005)). For forty years since its discovery, the origin of this feature and the nature of the carrier(s) have remained controversial. Our team used a transmission electron microscope, equipped with monochromator and high-resolution electron energy loss spectrometer, to study interstellar grains embedded within interplanetary dust particles (IDP's) that were collected in the stratosphere using NASA ER2 aircraft. They isolated the strong 5.7-electron volt (2175 angstrom) feature; the carriers are mixtures of organic carbon and amorphous silicates that are abundant in

both IDP's and in the interstellar medium. Thus the explanation for the ubiquitous 2175 angstrom line is: "the common stuff" of interstellar space, organic carbon and amorphous silicates.

The electron micrograph shows a glass embedded with metals and sulfides (GEMS), which are abundant in primitive cometary IDP's. We proposed that these are being formed from shock-accelerated crystalline dust in 'superbubbles', (formed by the winds from many massive stars and their explosions as supernovae). GEMS are proposed as the long-sought source material of Galactic Cosmic Rays - awaiting discovery in laboratories for over 30 years.

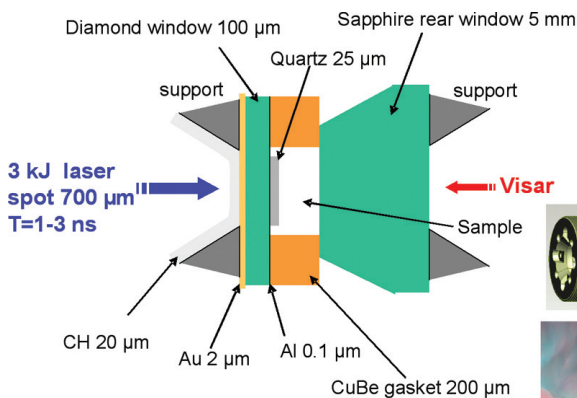
Laboratory Astrophysics

High Energy Density Laboratory Astrophysics

The properties of dense hydrogen, helium, and mixtures of the two, are needed to determine the internal structure of Jupiter. We want to answer questions like: is there a phase separation of H-He? Do He rain drops occur? Where is the convection zone? How and where is the magnetic field generated? The data we need is the equation of state, which relates pressure, temperature and density. The pressures needed are 100's of GPa, (millions of earth atmospheric pressures). We can produce these extreme pressures (equivalently high energy densities, as pressure is energy per unit volume) by shock compression; a laser ablates a surface and drives a shock-wave into the material we want to study. Different trajectories in (pressure,

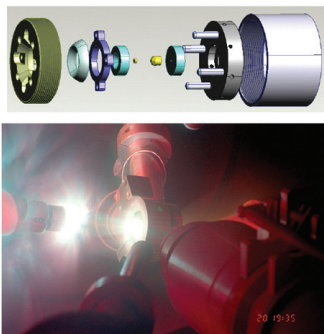
density) space are followed by pre-compressing the sample in a diamond anvil cell.

Measurements in real time are made of the shock velocity, emission and reflectance, and these give us data on insulating – conducting transitions, temperature, and the pressure – density curves. First results in pioneering this powerful technique for accessing high density states are in agreement with one of the existing astrophysical models. We have almost reached the point where pressure-induced ionization will be dominant for He. After studying different mixture of H_2 , He, we will move on to study the phase diagram of H_2 and He at higher pre-compressions ($\sim 5 - 10$ GPa), and use more powerful lasers.



Accurate determination of index of refraction n , sample thickness, and V_0 of sample at initial pressure is carried out for all samples prior to the experiment

The experimental layout used for the high energy density measurements of hydrogen and helium properties



The Physics and Advanced Technologies Directorate has a successful and continuing program in astrophysics R&D, both experimental and theoretical. The research areas are chosen for their tight coupling to the science of stockpile performance, the technology of national security, and the capabilities of LLNL. We are currently emphasizing four thrust areas:

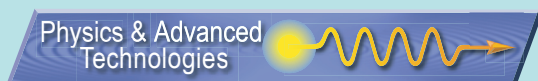
- **Stars from Birth to Death**
- **The Primitive Solar System**
- **Giant Planets**
- **The High Energy Universe**

Examples of experimental R&D include dual purpose detectors, surveillance, data handling and mining, and materials science techniques. Examples of theoretical R&D include radiation transport, radiation-hydrodynamics, and plasma physics.

There are opportunities for PostDocs as well as collaborative research, in many of the areas discussed.

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